Risks to Drinking Water from Oil and Gas Wellbore Construction and Integrity

Case Studies and Lessons Learned

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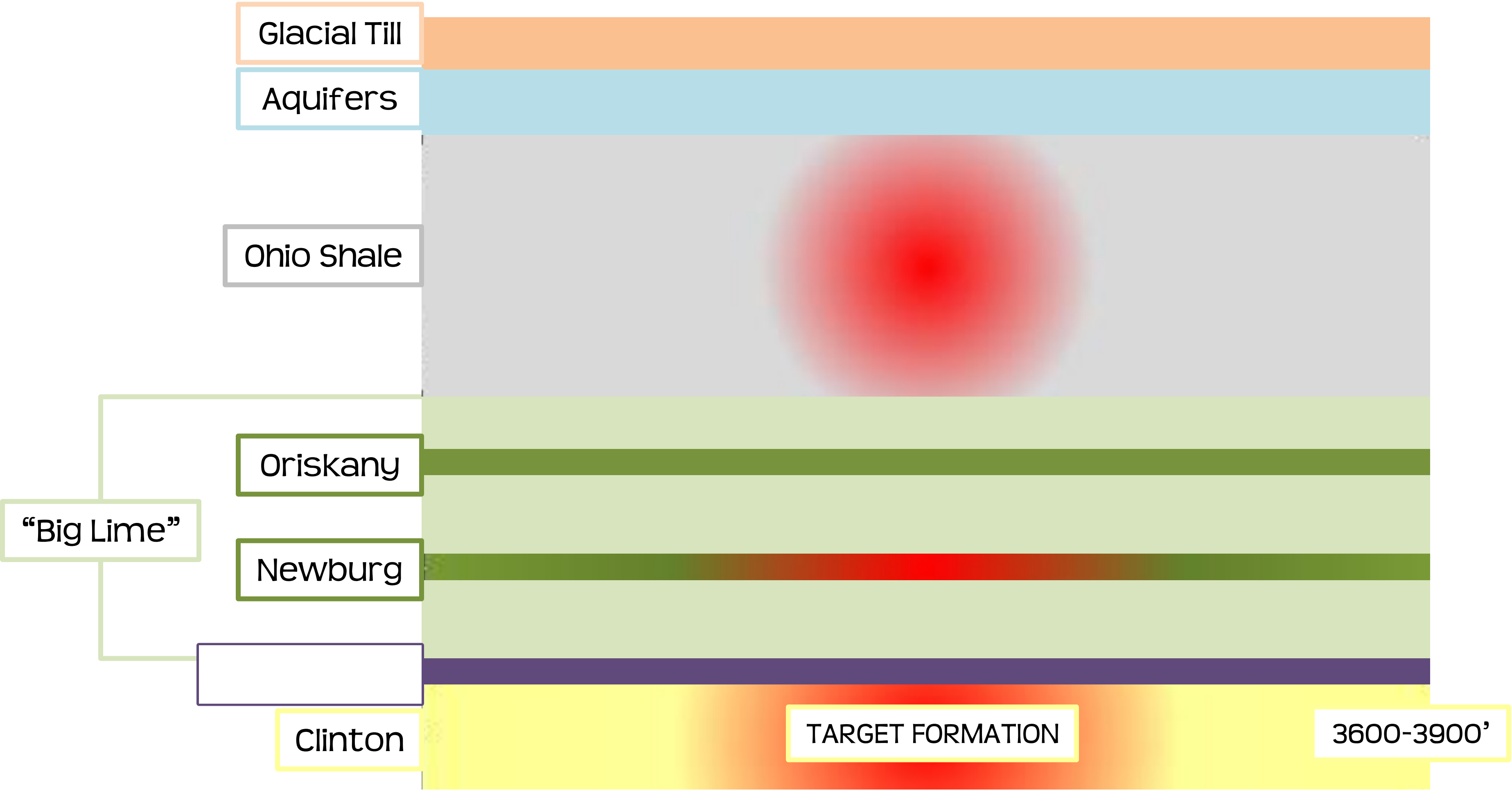
Case Study 1

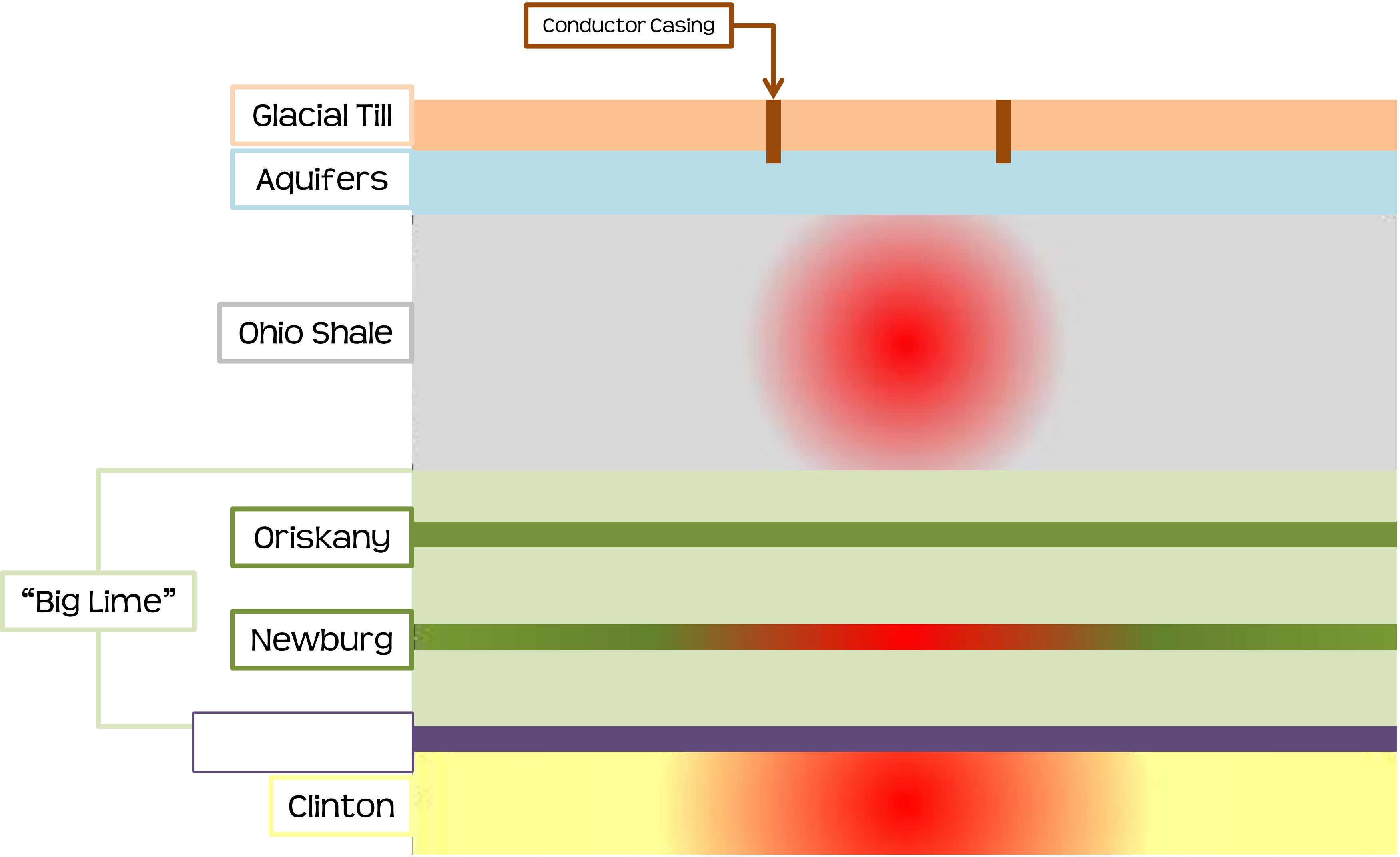
BAINBRIDGE TOWNSHIP, OHIO

Incident Summary

- December 15, 2007: Explosion at a home in Bainbridge Township, Geauga County, OH
- Investigators determine natural gas is entering homes via water wells
- Ohio Department of Natural Resources, Division of Mineral Resources Management (DMRM) evaluates local oil and gas wells to determine source of natural gas
- Ohio Valley Energy Systems Corp (OVESC) identifies problems with their English No. 1 well, assumes responsibility for incident, and initiates corrective action
- DMRM initiates monitoring program, measures response of water wells to corrective action at the English No. 1, performs remedial water well work, provides methane monitoring equipment to 49 homes, and provides replacement drinking water to 48 homes.

Simplified Stratigraphy at English No. 1

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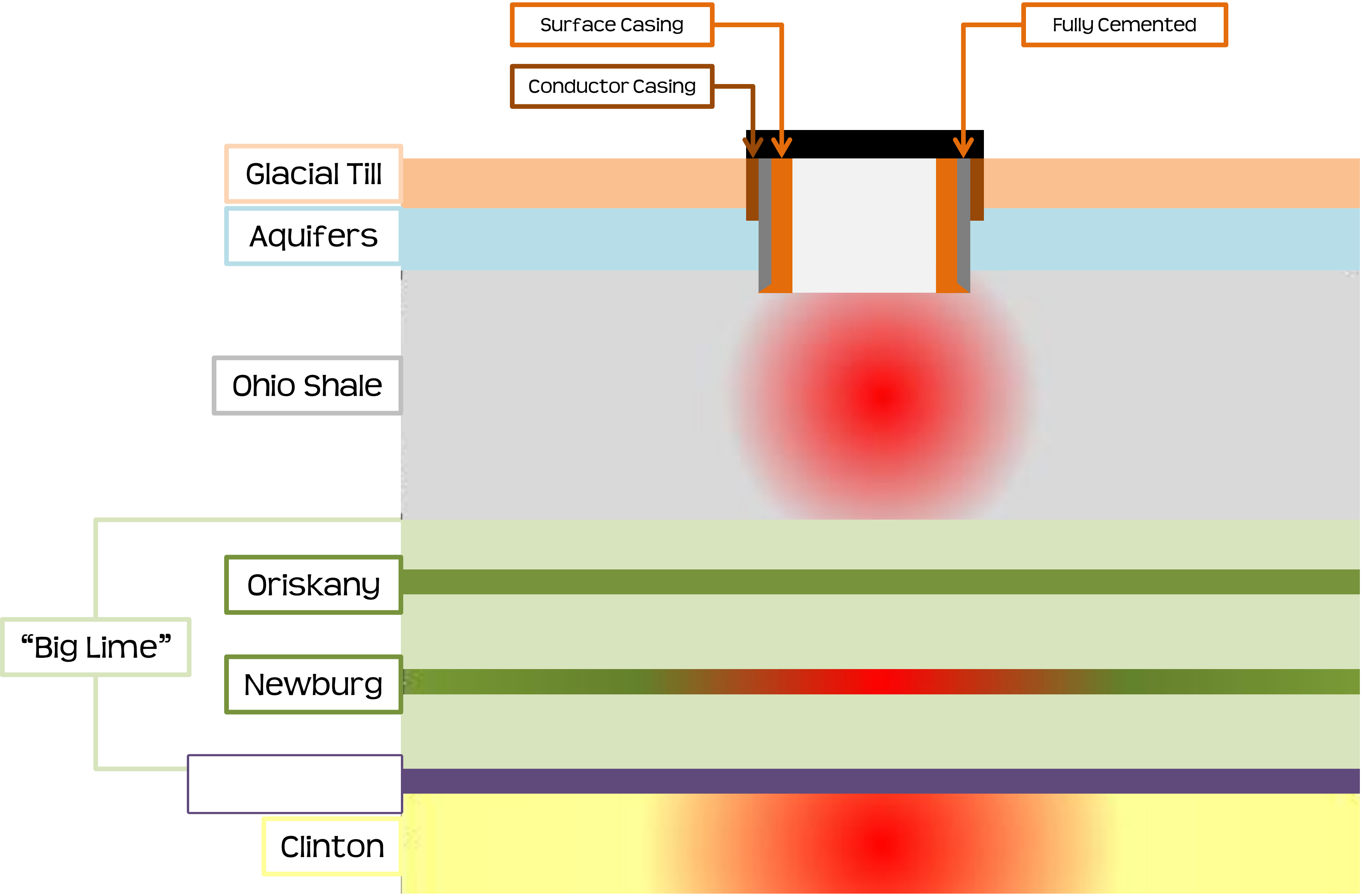
Newburg
Clinton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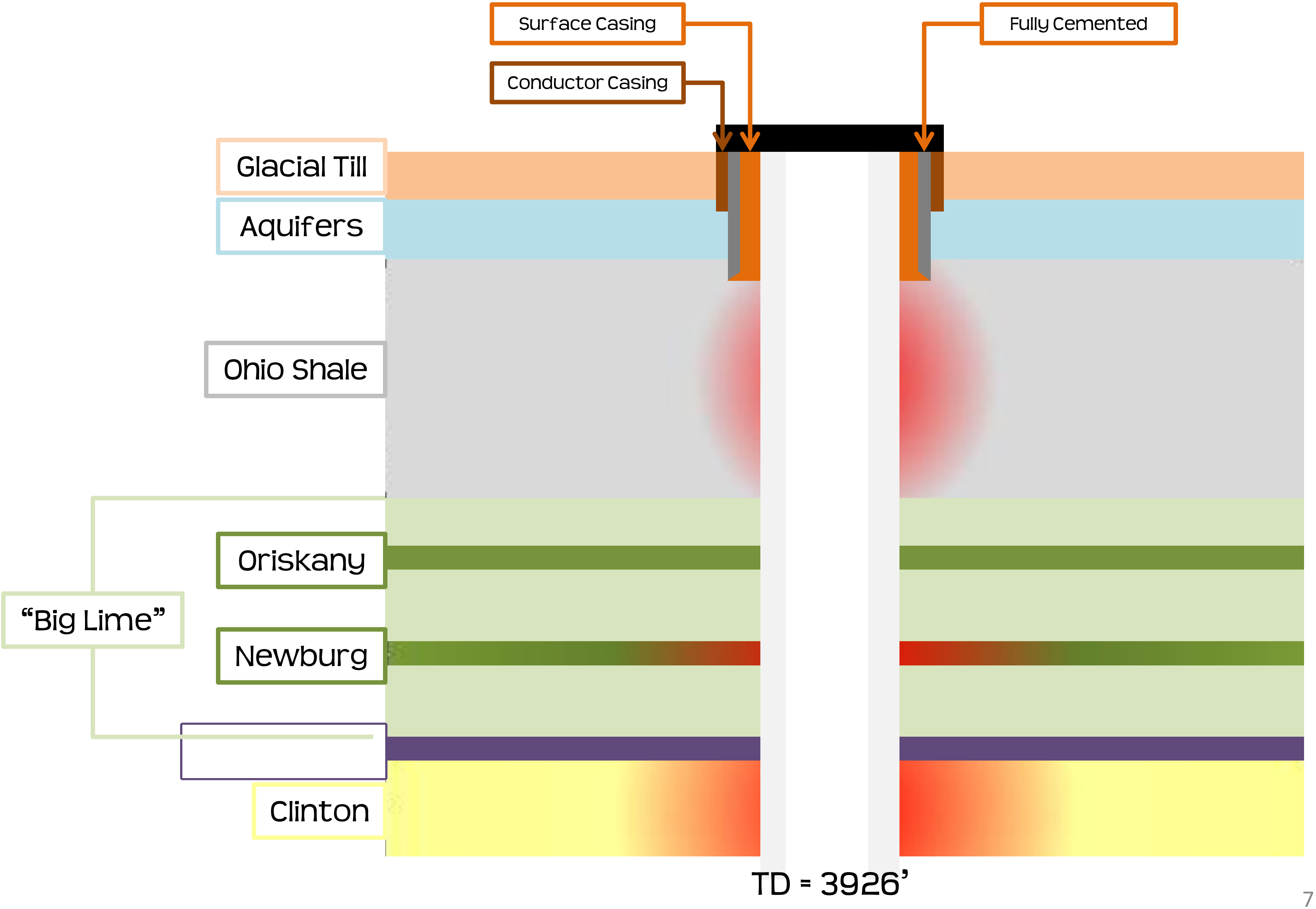
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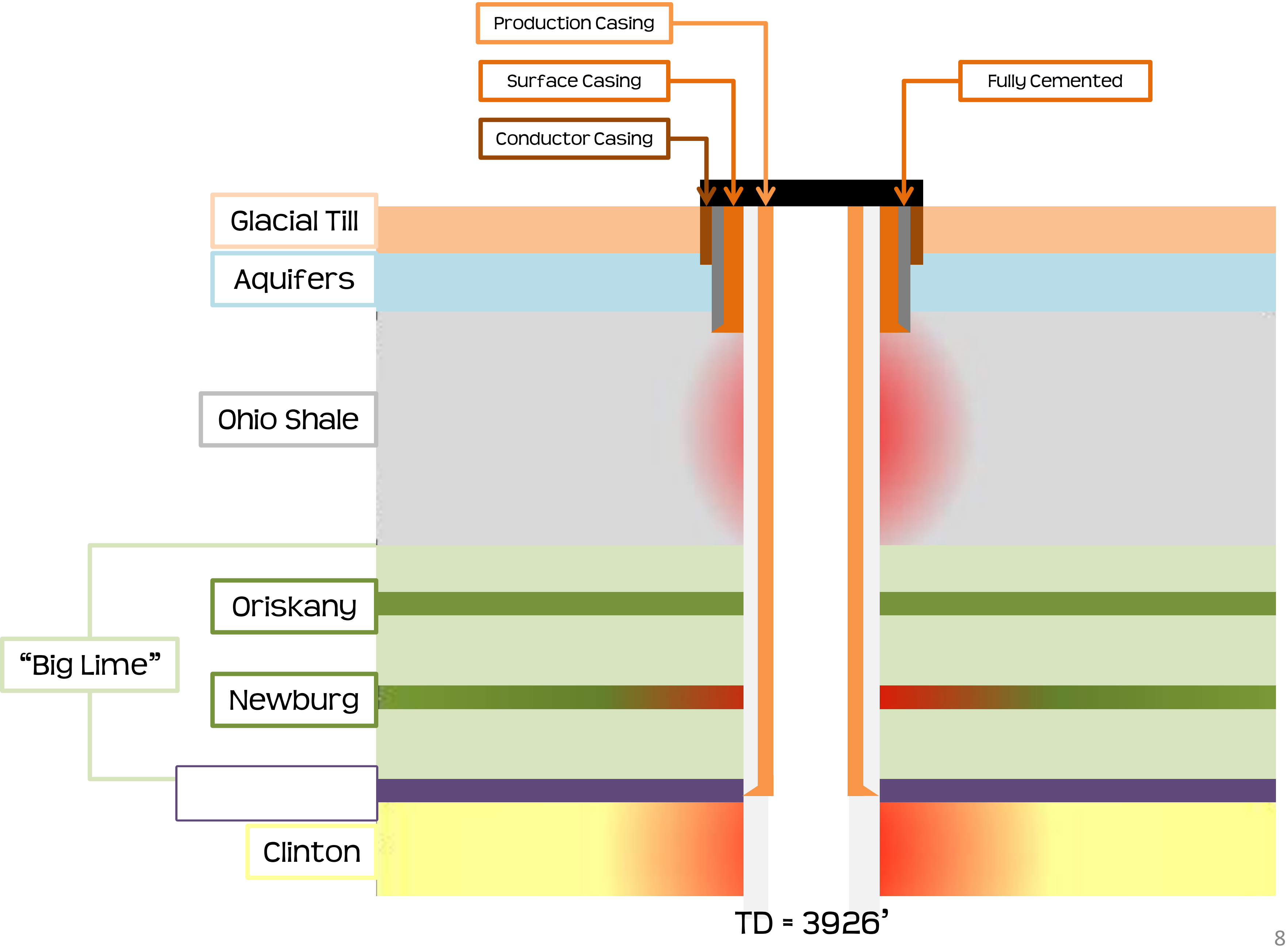
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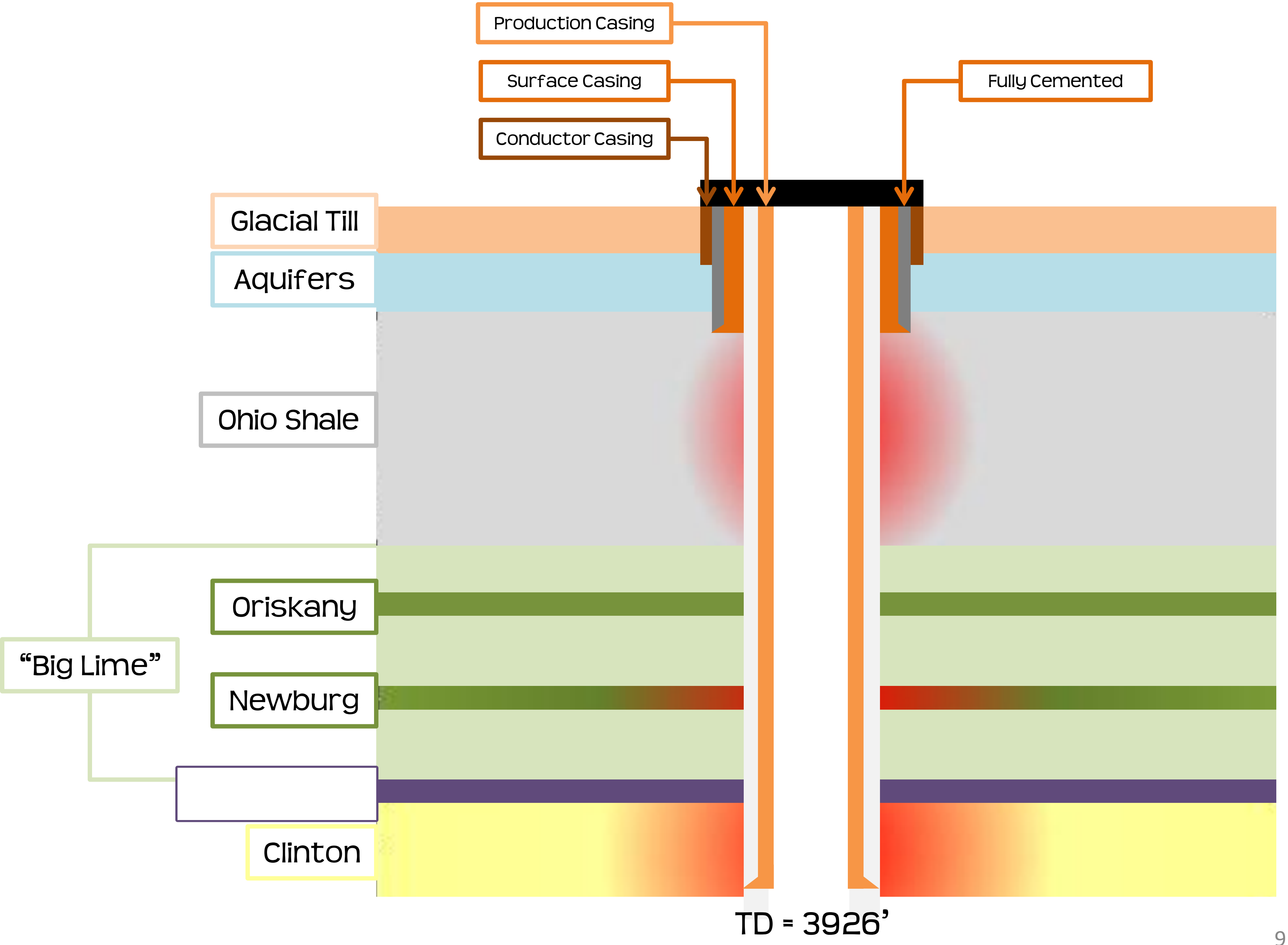
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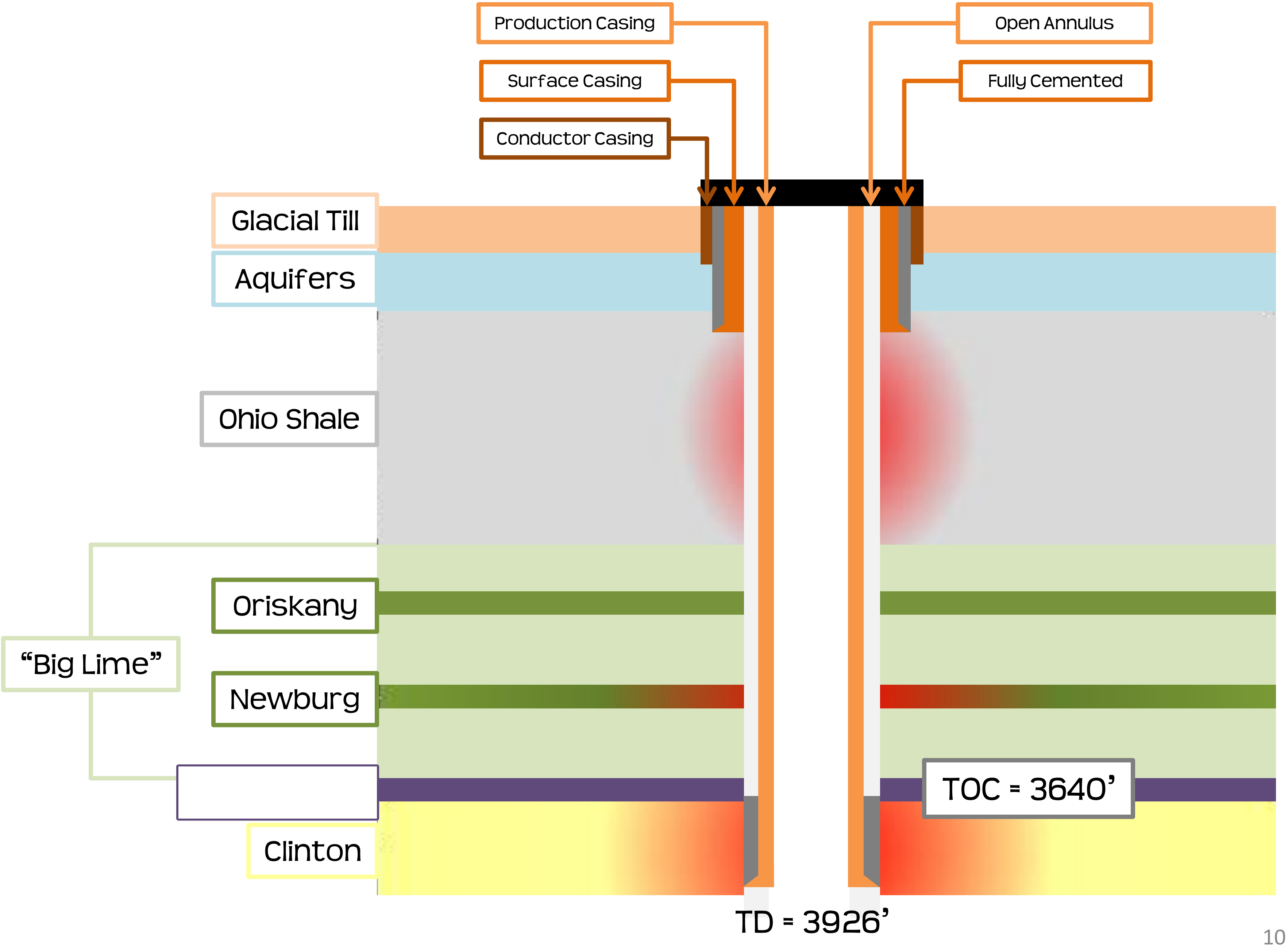
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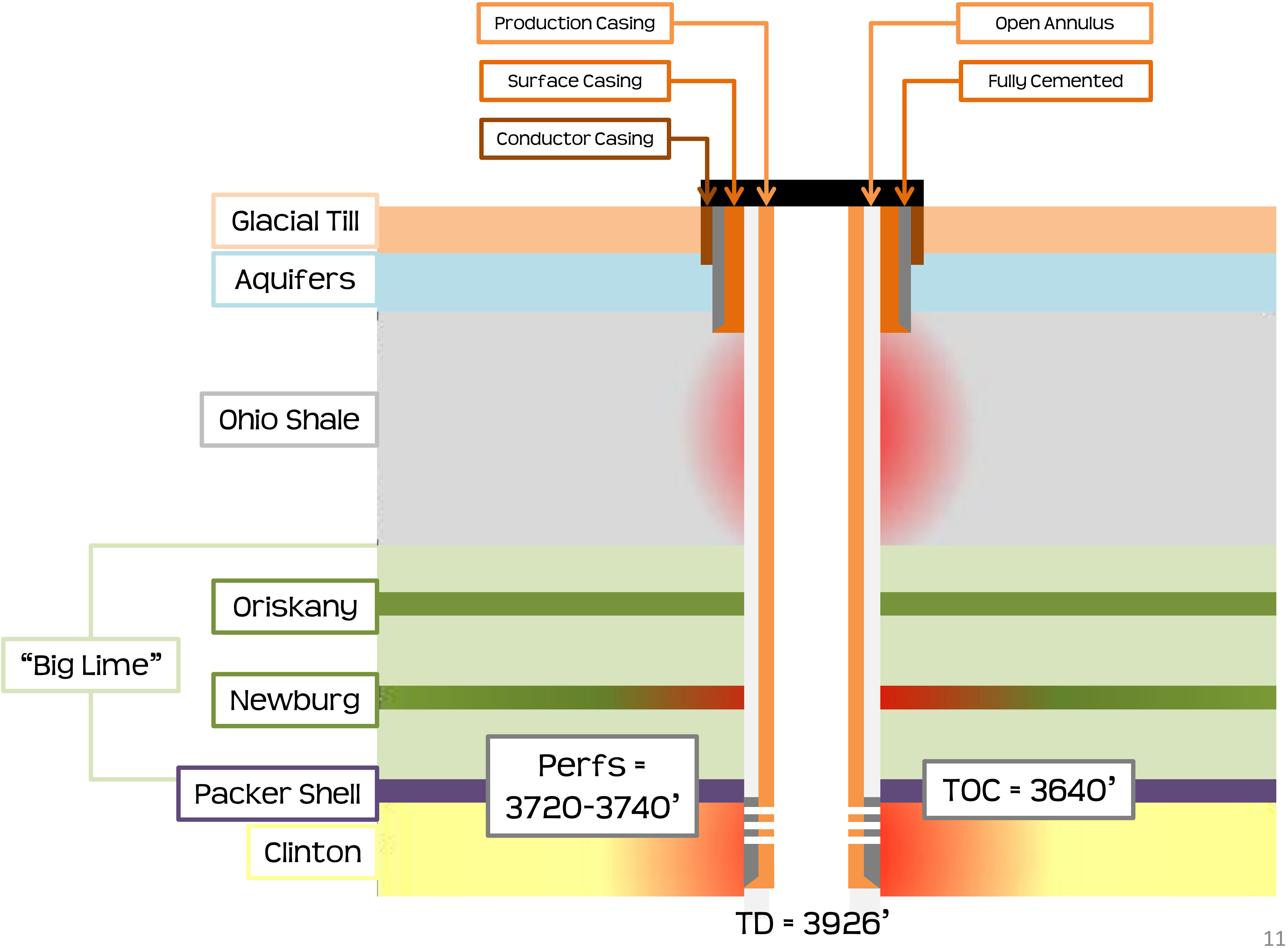
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Newburg
Packer Shell
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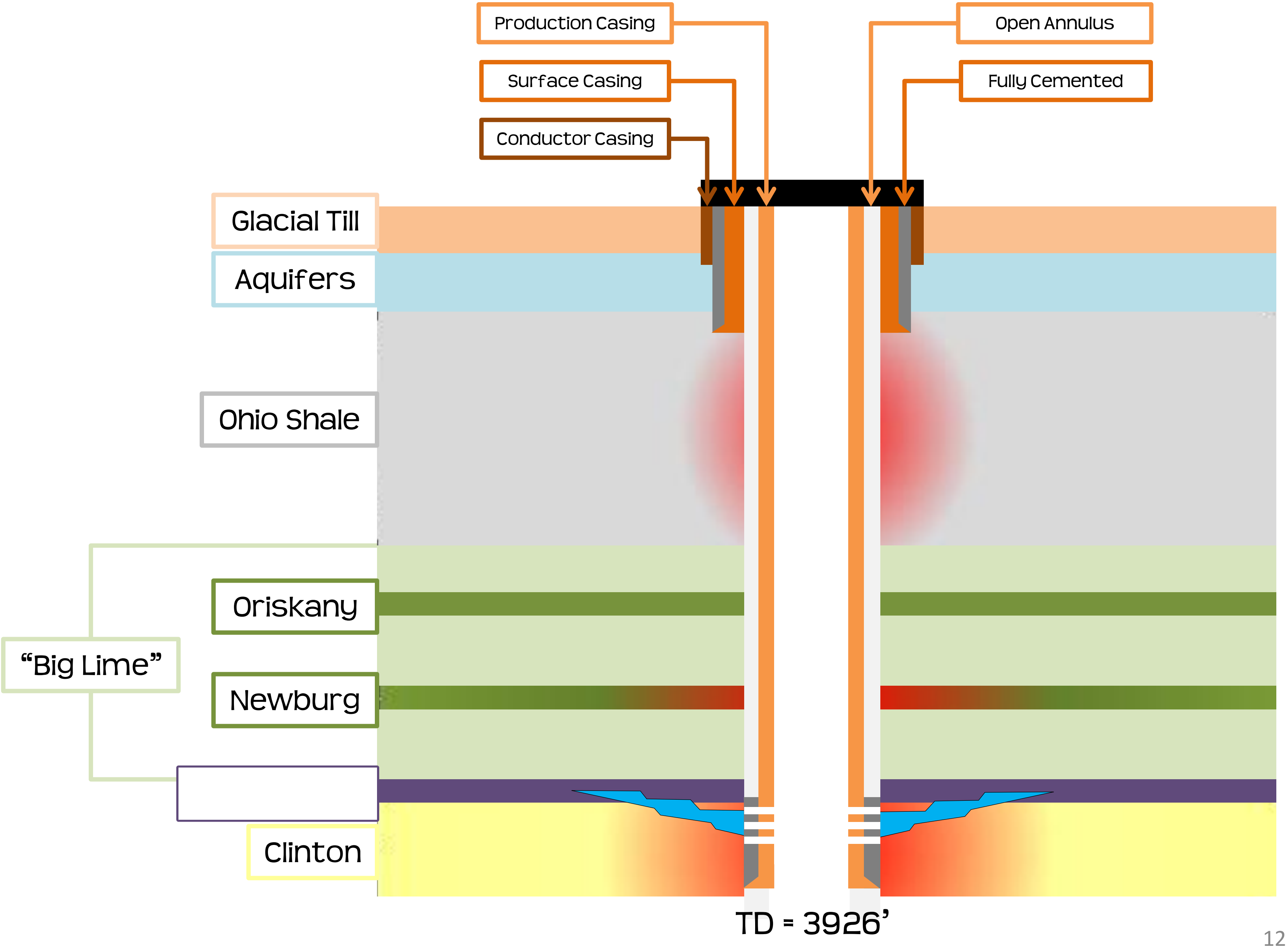
TOC = 3640'
TD = 3926'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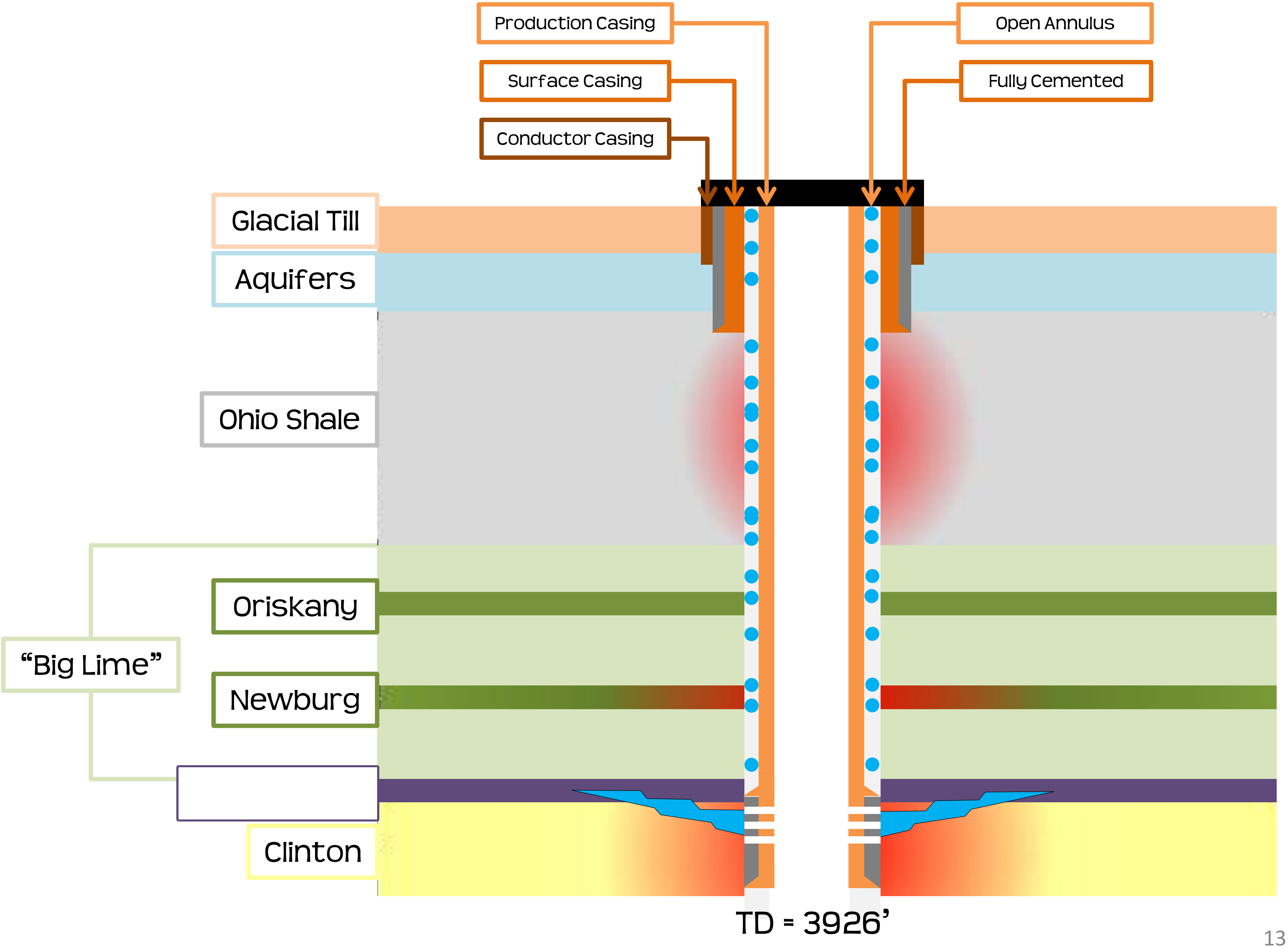
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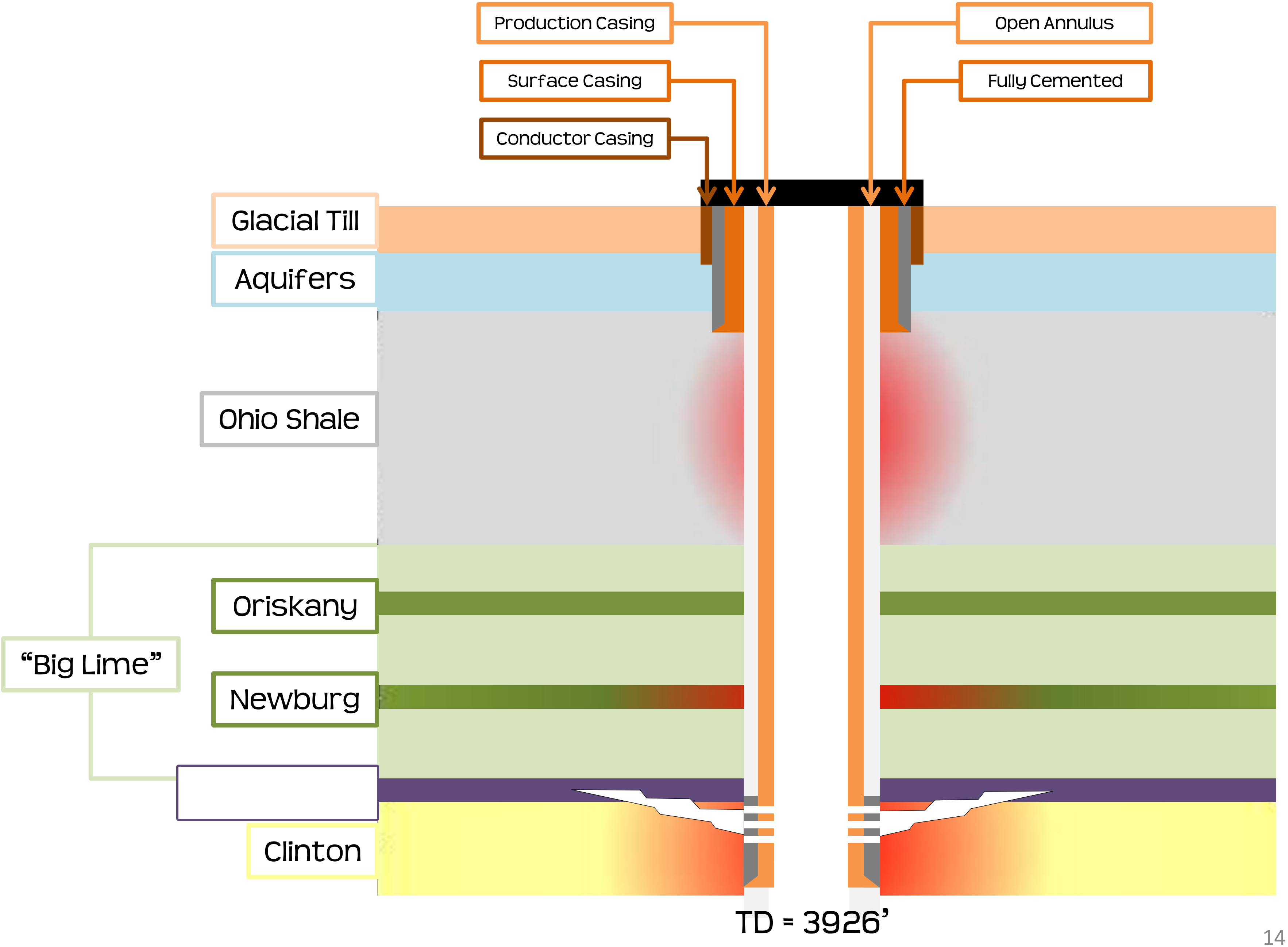
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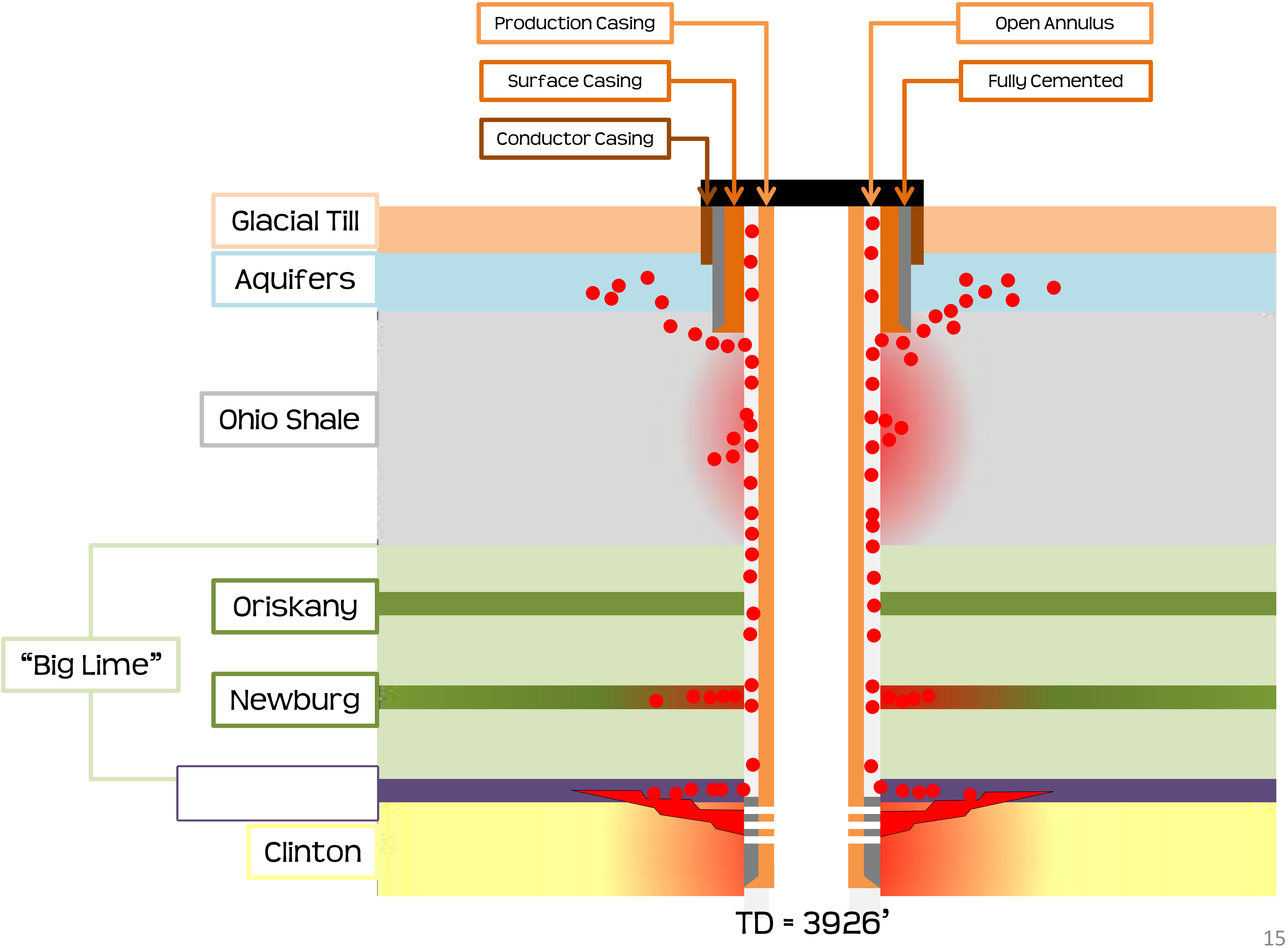
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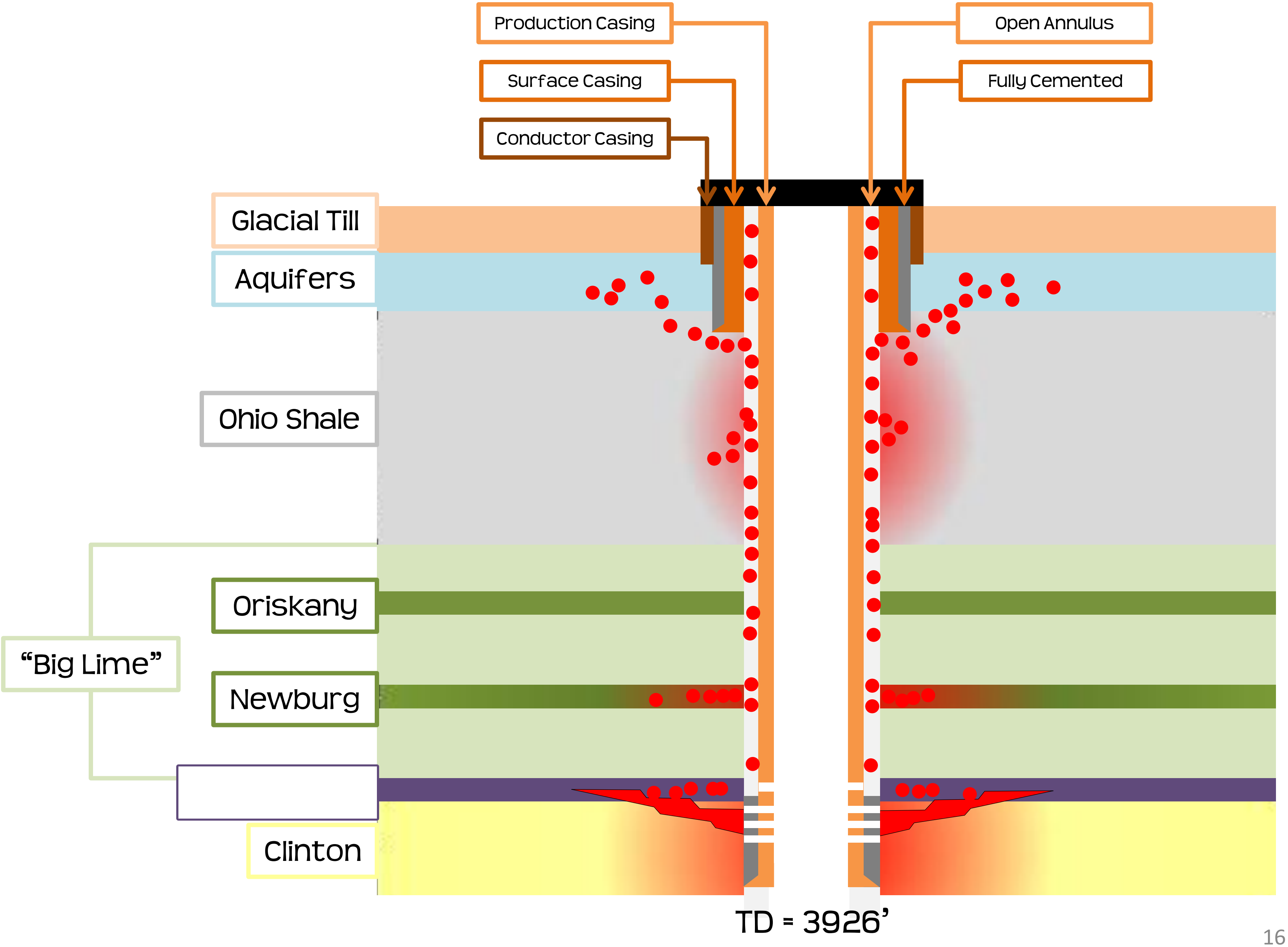
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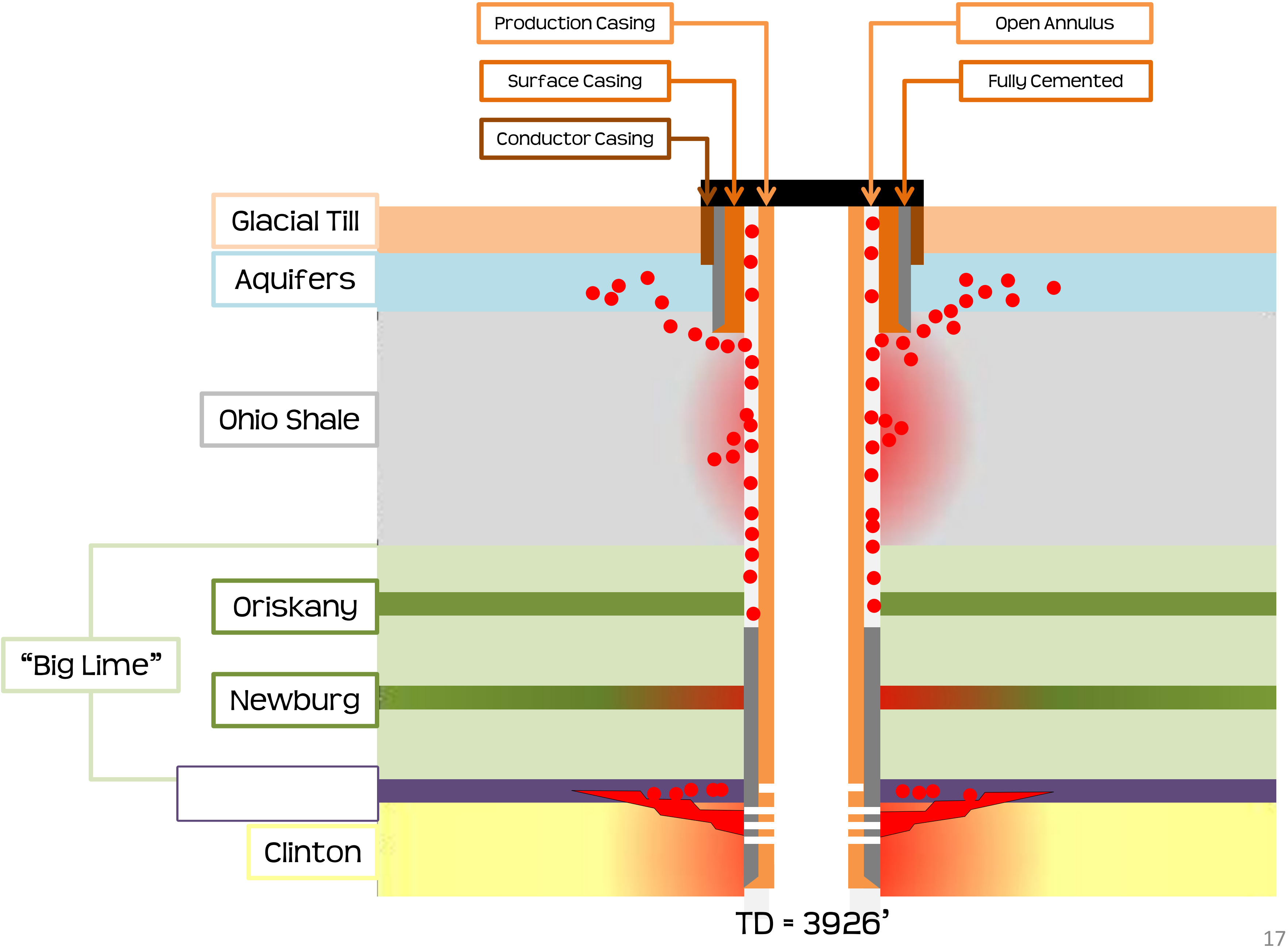
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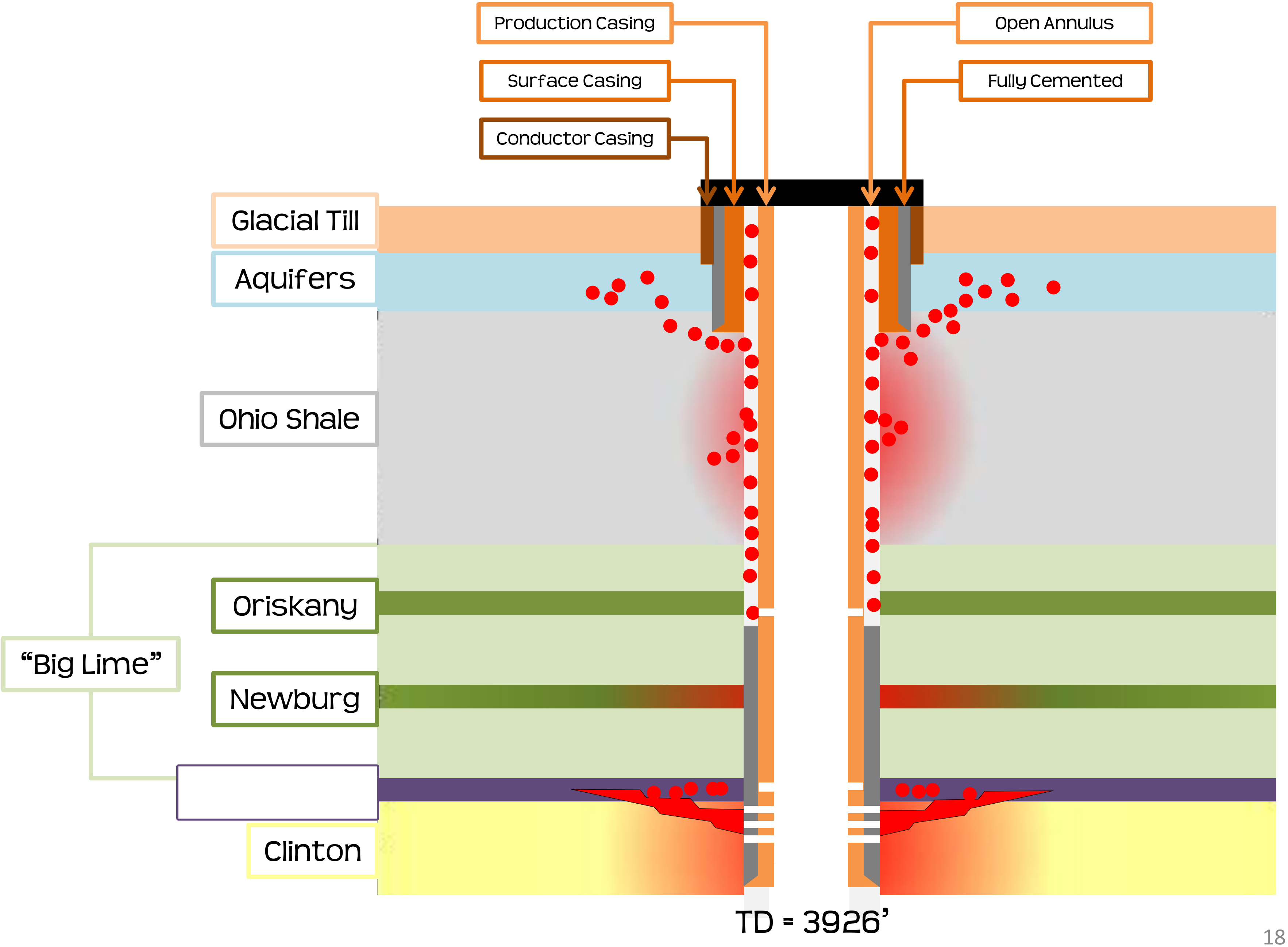

Production Casing

Open Annulus

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Fully Cemented

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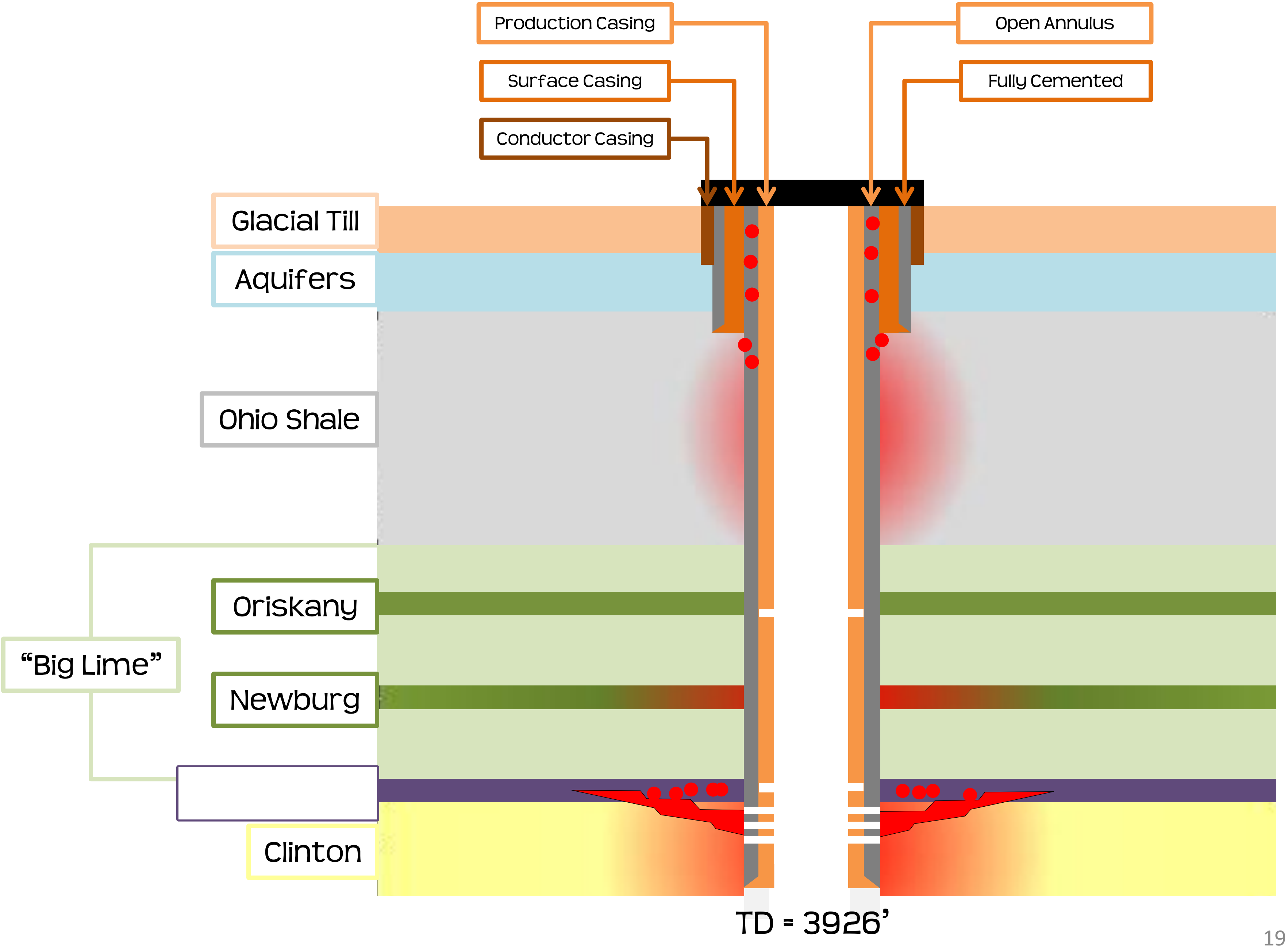

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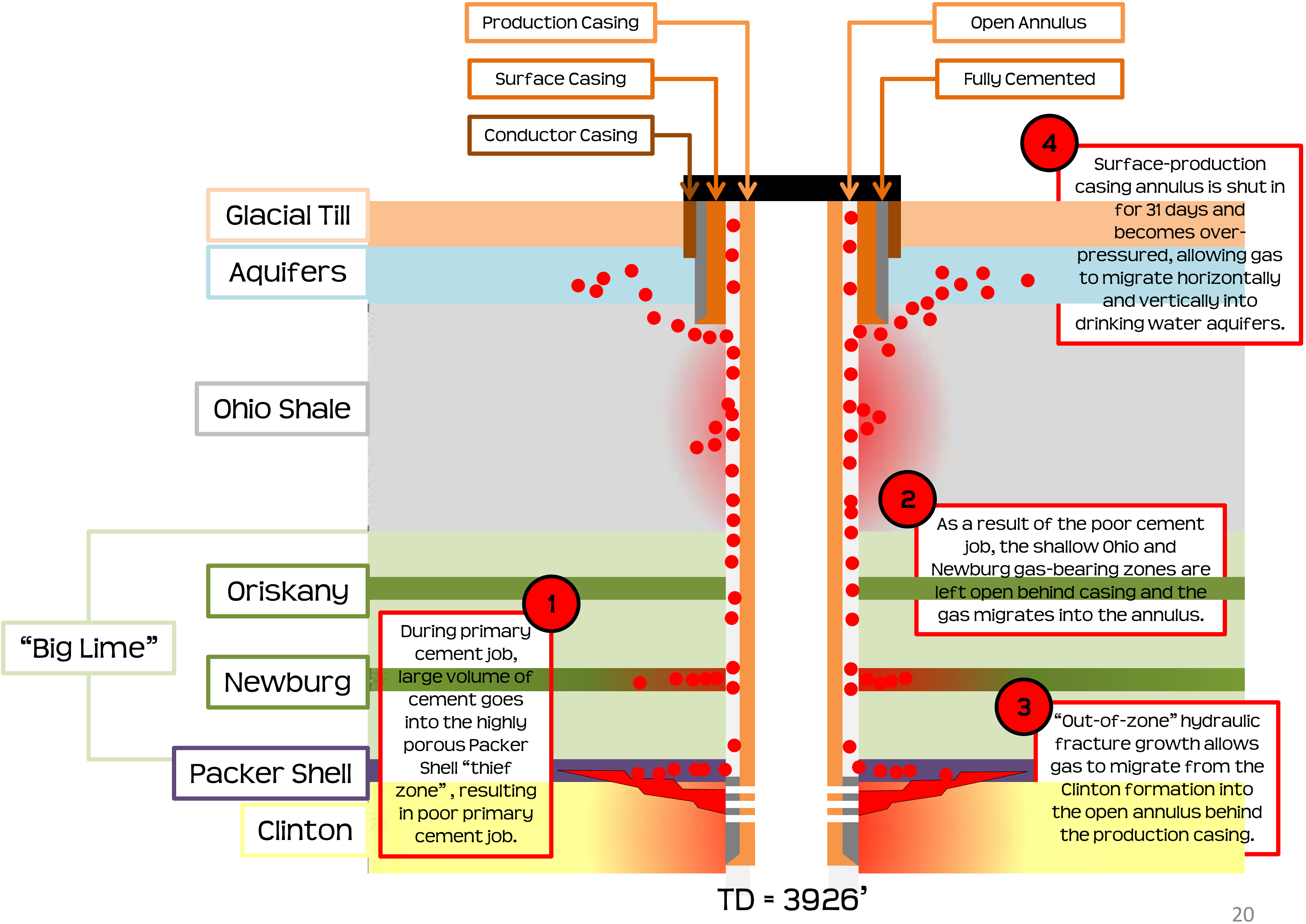


① During primary cement job, large volume of cement goes into the highly porous Packer Shell "thief zone", resulting in poor primary cement job.

② As a result of the poor cement job, the shallow Ohio and Newburg gas-bearing zones are left open behind casing and the gas migrates into the annulus.

③ "Out-of-zone" hydraulic fracture growth allows gas to migrate from the Clinton formation into the open annulus behind the production casing.

④ Surface-production casing annulus is shut in for 31 days and becomes over-pressured, allowing gas to migrate horizontally and vertically into drinking water aquifers.

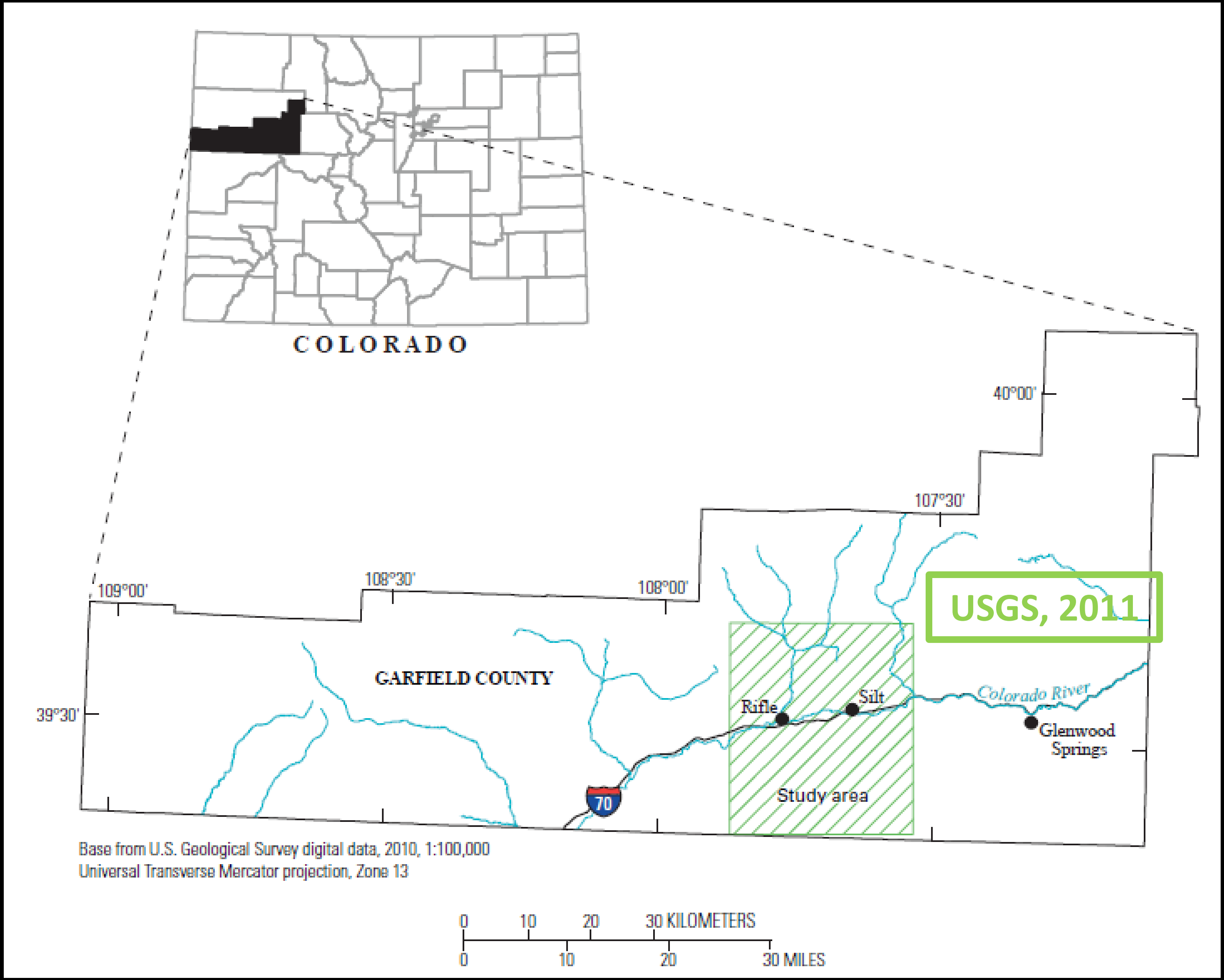
Areas of Dispute

- Was the over-pressurization of the annulus sufficient to fracture the geologic units exposed in the wellbore?
- If so, could these fractures create a permanent migration path for gas to reach groundwater?
- Can methane gas concentrations in domestic water wells be used to delineate such fracture networks?
- What is the nature and origin of the presence of black particulate matter in some domestic water wells?

Case Study 2

MAMM CREEK FIELD, GARFIELD COUNTY, COLORADO

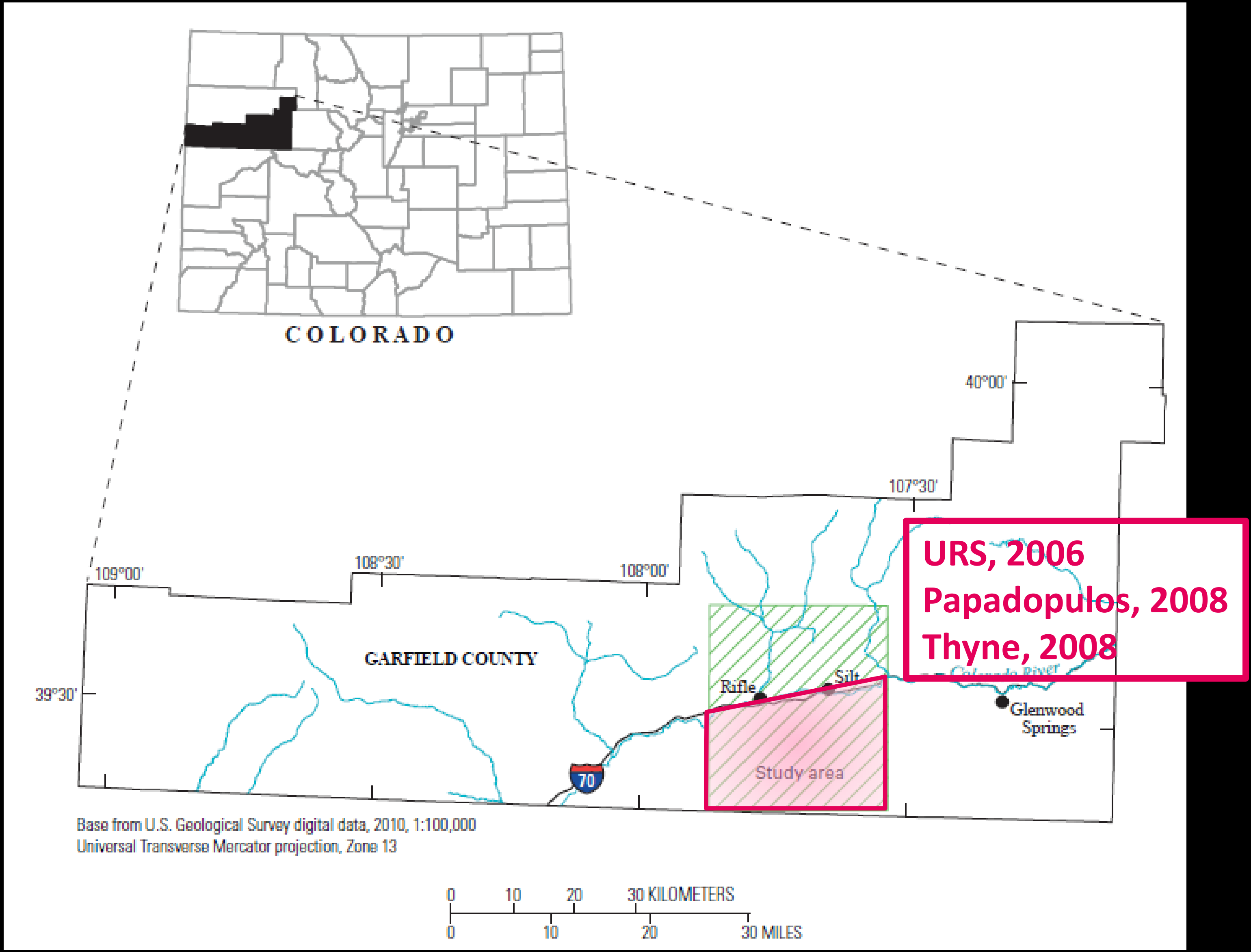
Study Area



USGS, 2011

Source: USGS 2011

Study Area



Base from U.S. Geological Survey digital data, 2010, 1:100,000
Universal Transverse Mercator projection, Zone 13

URS, 2006
Papadopulos, 2008
Thyne, 2008

Source: USGS 2011

Incident Summary

- West Divide Creep Seep: COGCC detects BTEX compounds, methane, and heavy hydrocarbons (C2-C6) in West Divide Creek resulting from a poor cement job in a nearby gas well

- Due to water contamination incidents and increased gas drilling, Garfield County, CO commissions a series of studies to assess the risks to surface and groundwater from gas well development and human activities

- The United States Geological Survey (USGS), in cooperation with the Colorado Department of Public Health, also undertakes a study to determine the sources and sinks of nitrate and methane in Garfield County domestic water wells

- Sampling of domestic water wells shows elevated concentrations of methane; groundwater quality health standards are exceeded for fluoride, selenium, nitrate, and arsenic; aesthetic standards are exceeded for chloride, iron, manganese, and total dissolved solids (TDS).
  - Fluoride and selenium do not appear to be related to oil and gas activity
  - Nitrate concentrations most likely related to agricultural activity, septic system effluent, and animal waste
  - Domestic water well hydrogeochemistry shows evidence of mixing between shallow groundwater and deep formation water in some wells

Areas of Dispute

- Temporal correlation of methane and chloride contamination and natural gas activity
- Nature and origin of methane in water wells
  - Thermogenic vs. Biogenic
  - Related to natural gas extraction?
- Primary mechanism for deep Wasatch and/or Mesaverde formation water to mix with groundwater

Nature and Origin of Methane in Groundwater

STUDY	METHANE TYPE	ORIGIN	TRANSPORT
URS, 2006	Biogenic	Biogenic origin	Not discussed
URS, 2006	Thermogenic	Thermogenic origin	• Natural fractures • Gas drilling and production activities/ improperly abandoned wells
URS, 2006	Mixed/Unknown	Uncertain origin	Possible mixed sources
Papadopulos, 2008	Biogenic	Biogenic origin	Indeterminate
Papadopulos, 2008	Thermogenic	Conventional thermogenic, coalbed thermogenic, oxidized biogenic, or mixing	Indeterminate
Thyne, 2008	Thermogenic	Conventional thermogenic or Microbial reduction of thermogenic Mesaverde CO_2 to CH_4	Gas drilling and production activities
USGS, 2011	Biogenic	Deep Wasatch	•Natural fractures •Uncemented gas well annuli
USGS, 2011	Thermogenic	Mesaverde thermogenic and oxidized biogenic	•Natural fractures •Uncemented gas well annuli

Nature and Origin of Water Types

STUDY	WATER TYPE	ORIGIN	TRANSPORT
URS, 2006	$Na/Ca/Mg\text{-}HCO_3$	Shallow groundwater	Precipitation/recharge
URS, 2006	$Na\text{-}SO_4$; $Na\text{-}SO_4\text{-}HCO_3$	Unknown	Unknown
URS, 2006	Na-Cl	Deep groundwater	• Fracture zones/structural features • Gas wells
Papadopulos, 2008	Mixed cation-bicarbonate anion, low TDS	Shallow groundwater	Precipitation/recharge, flow along shallow pathways
Papadopulos, 2008	$Na\text{-}HCO_3$; $Na\text{-}SO_4$ (high TDS)	Shallow or deep groundwater	• Precipitation/recharge, flow along shallow pathways • Vertical upward flow along natural fractures, wellbores, or hydraulic fractures
Papadopulos, 2008	Na-Cl	Deep groundwater/brine	• Natural deeper flow processes
Thyne, 2008	Low TDS, Ca-Na-Mg-HCO3	Streams and water wells near surface streams	Precipitation/recharge
Thyne, 2008	Higher TDS, Na-Ca-HCO3-SO4	Water wells, deeper/not near streams	Precipitation/recharge
Thyne, 2008	Higher TDS, Na-Cl	Williams Fork Formation (Mesaverde) produced water	Gas drilling and production activities
USGS, 2011	High-oxygen, high-nitrate, low-methane; mixed cation-SO4-HCO3, mixed cation-HCO3-SO4; young or mixed age	Shallow groundwater (Evidence in some wells of septic system effluent, animal waste, fertilizer)	Precipitation/recharge
USGS, 2011	High-oxygen, high-nitrate, low-methane; mixed cation-SO4-HCO3, mixed cation-HCO3-SO4; old	Deeper groundwater (not Mesaverde)	Precipitation/recharge
USGS, 2011	Low-oxygen, low-nitrate, high-methane; Na-HCO3 to Na-Cl; mixed age or old	Primarily Mesaverde formation water mixed w/some shallow groundwater	•Natural fractures •Uncemented gas well annuli

Key Observations

- The study area is naturally faulted and fractured. Fault and fracture density increases near structural features, such as the Divide Creek Anticline

- For new wells:
  - Surface casing must be set below the lowest USDW and cemented to surface
  - Production casing must be cemented to 500’ above the top of gas in the Mesaverde (Williams Fork)
  - The deep Wasatch may be left open to the annulus
  - Older wells may have been constructed using different standards

- Gas production wells with persistent or recurring elevated bradenhead pressures have been identified near structural features

- Domestic water wells with elevated methane and chloride concentrations are often coincident with structural features

- Natural fractures and faults may
  - Provide natural migration pathways for gas and fluids, both to groundwater and to the uncemented annular space of wellbores
  - Cause complications in well drilling, construction, and completion

Challenges

- “Most water supplies within the Bainbridge investigation area do not have water analyses predating local oil and gas activities.” (DMRM, 2008)

- “Due to the absence of historic water quality data prior to drilling of gas wells to serve as a baseline in the area, the water quality issues observed in the study area could predate gas well drilling activities. We cannot make a definitive statement other than the water quality issues could be caused by natural conditions and/or potentially the presence of gas wells in the area.” (URS 2006)

- “Domestic wells (are) not placed to determine sources of contamination in groundwater. They are not evenly spaced around gas wells or within close enough proximity to determine the presence of chemicals associated with methane that degrade rapidly.” (Thyne, 2008)

- Construction and abandonment practices for older wells may pose a higher risk for migration of methane to groundwater. (Papadopulos, 2008)

- “The cementing problems encountered at the Schwartz 2-15B gas well are evidence that the presence of fractured intervals in this area may also affect cement integrity in gas well completions” (URS, 2006)

- “The effect on groundwater due to the introduction of drilling or well completion/hydrofracturing fluids into the shallow aquifer was not investigated for this study. A study evaluating possible local effects of drilling or hydrofracturing fluids on domestic groundwater should be considered.” (Papadopulos, 2008)

Solutions & Lessons Learned

- Detailed site characterization and planning
  - Geologic and hydrologic
  - Baseline water chemistry
  - Gas sampling and composition (vertical and aerial)
  - Temporal and aerial updates
- Wellbore construction and maintenance
  - Hydrocarbon and brine bearing zones must be isolated
  - Wellbore integrity and workovers
- Water quality monitoring plan and dedicated monitoring wells
- Hydraulic fracture modeling and measurement
- Must consider cumulative impacts

References

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- McMahon, P.B., Thomas, J.C., and Hunt, A.G., 2011, Use of diverse geochemical data sets to determine sources and sinks of nitrate and methane in groundwater, Garfield County, Colorado, 2009: U.S. Geological Survey Scientific Investigations Report 2010 5215, 40 p.
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- Papadopulos & Associates, Inc., 2008, Phase II hydrogeologic characterization of the Mamm Creek Field area, Garfield County, Colorado: Prepared for the Board of County Commissioners, Garfield County, Colorado, 41 p.
- Papadopulous & Associates, Inc., 2009, Evaluation of Thyne, 2008 "Review of Phase II Hydrogeologic Study" Mamm Creek Field Area, Garfield County, Colorado: PowerPoint presentation prepared for the Colorado Oil & Gas Conservation Commission, 29 p., http://cogcc.state.co.us/Library/Presentations/Glenwood_Spgs_HearingJuly_2009/(1_D)_Evaluation_of_Thyne_Report_vers2%20(dv).pdf
- Thyne, Geoffrey, 2008, Review of Phase II Hydrogeologic Study prepared for Garfield County: Prepared for Garfield County, 26 p., http://cogcc.state.co.us/Library/Presentations/Glenwood_Spgs_HearingJuly_2009/(1_A)_ReviewofPhase-II-HydrogeologicStudy.pdf
- URS Corporation, 2006, Phase I hydrogeologic characterization of the Mamm Creek Field area in Garfield County: Prepared for the Board of County Commissioners, Garfield County, Colorado, 86 p.

Risks to Drinking Water from Oil and Gas Wellbore Construction and Integrity: Case Studies and Lessons Learned

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Natural Resources Defense Council

Introduction

Numerous cases of known or suspected drinking water contamination across the country have been linked to oil and gas production. This paper will examine various published reports from two such cases and discuss the potential roles of wellbore construction and integrity and hydraulic fracturing in the resultant drinking water contamination.

Case Study #1: Bainbridge Township, Geauga County, Ohio

Incident Summary

On December 15th, 2007, an explosion was reported in the home at 17975 English Drive, Bainbridge Township, Geauga County, Ohio. Early investigations determined that methane was entering homes in the vicinity of the explosion through domestic water wells. The Ohio Department of Natural Resources, Division of Mineral Resources Management (DMRM) inspected local gas wells to identify the source of the gas. When inspectors arrived at the English No. 1 gas well owned by Ohio Valley Energy Systems Corp (OVESC), representatives from OVESC were on location examining the well and discussing remedial cementing operations. OVESC proactively assumed responsibility for the incident without waiting for a completion of the investigation by DMRM and initiated corrective action. In the weeks following the explosion, DMRM initiated a monitoring program for methane in wells and homes and to monitor the response of wells to corrective action at the English No. 1 well. DMRM performed remedial work on affected water wells and provided in-home methane monitoring systems and replacement sources of drinking water for affected homes (Ohio DNR DMRM, 2008).

Simplified Stratigraphy at the Location of the English No. 1 Well

The OVESC English No. 1 well was drilled to a total depth of 3,926’. The formations encountered during drilling, listed in order of increasing depth, are as follows (Ohio DNR DMRM, 2008):

- Unconsolidated glacial till. Less than 88’ thick
- Pennsylvanian and Mississippian aged interbedded sandstone and shale comprising the drinking water aquifer: Sharon Conglomerate, Cuyahoga Formation, Berea Sandstone. The Berea Sandstone has sometimes been noted to contain low-pressure natural gas. Approximately 200’ thick
- Devonian aged Ohio Shale. Contains noncommercial quantities of low-pressure natural gas. Approximately 1800 feet thick

- Devonian and Silurian aged “Big Lime”/Lockport Dolomite limestone and evaporate deposits. Contains the Oriskany Sandstone and “Newburg” Dolomite members, which are porous, permeable, brine-bearing zones which sometimes locally contain noncommercial quantities of natural gas. Approximately 1600’ thick
- Thin interbedded shale and limestone partly comprising the seal for the gas-bearing target reservoir. Contains the Packer Shell, a typically impermeable limestone but which can be locally faulted or fractured near structural features. Approximately 100’ thick
- Low porosity and permeability Clinton Sandstone. Target formation containing commercial quantities of natural gas. Approximately 200’ thick

Sequence of Events Leading to Natural Gas Invasion into Drinking Water Aquifers

OVESC spud the English No. 1 well on October 18th, 2007. Conductor casing was installed to a depth of 88 feet, through glacial till and into bedrock. The well was drilled through the groundwater aquifers and surface casing was set at 263 feet and cemented to surface. Drilling continued until the total depth of the well, 3,926 feet, was reached on October 26th. An open-hole logging run was attempted but the logging tool bridged out at 3,658 feet, the depth of the Packer Shell, due to an apparent filter cake build up. The logging tool could not be moved below the bridge and open-hole logs were not obtained. OVESC proceeded to set 4-1/2” production casing. Casing was run into the hole and became stuck at 3,659 feet, the depth of the Packer Shell. The casing was washed down to 3,873 feet, became differentially hung, and could not be lowered further. OVESC then proceeded to cement the production casing. Prior to cementing, circulation of the wellbore was established but was subsequently lost during the cementing operation and could not be re-established. The cementing operation was concluded and, due to the lost circulation event, a cement bond log was run to establish the top of cement (TOC). (Ohio DNR DMRM, 2008; Bair et al, 2010)

Based on the cement job design, TOC should have been 700-800 feet above the top of the Clinton formation. The cement bond log revealed TOC to be at 3,640 feet, the depth of the Packer Shell. This finding and the previous drilling, logging, and casing problems suggest the Packer Shell thieved a large quantity of cement due to the presence of localized fracturing. Despite the inadequate primary cement job, OVESC continued to complete the well. The well was perforated from 3720-3740 feet, leaving only approximately 80 feet of cement covering the Clinton between the top perf and the TOC/open annulus, and the planned hydraulic fracture treatment proceeded on November 13th. The original frac design called for 105,000 gallons of water and 600 sacks of proppant. After pumping less than half the planned fluid and proppant, fluid circulated out of the open valve on surface-production casing annulus. Pump pressure and rate were reduced, 4000 gallons of fresh water was pumped to flush and recover sand, and the frac job was discontinued. (Ohio DNR DMRM, 2008; Bair et al, 2010)

In the three days following the well completion, most of the frac fluid was recovered and pressure on the surface-production casing was recorded. The pressure increased each day and stabilized at 320 psi on the third day and gas was periodically blown off to reduce pressure. Construction was completed and the well was shut in for the next 31 days. (Ohio DNR DMRM, 2008; Bair et al, 2010)

While the well was shut in, gas from the Clinton, Newburg, and Ohio Shale formations migrated into the uncemented annular space behind the production casing and caused the annulus to become overpressured, reaching a maximum recorded pressure of 360 psi. This gas then migrated from the high-pressure annulus, through fractures, into the shallow low-pressure aquifer and subsequently into domestic water wells, culminating in the explosion on English Drive. (Ohio DNR DMRM, 2008; Bair et al, 2010)

Remedial Action

OVESC performed two remedial cement jobs, one to seal the annulus from the current TOC to above the Newburg formation and one to seal the remaining open annulus to surface. Small amounts of gas were still detected in the annulus and a segmented bond log was run to determine the source. The bond log showed channeling of the cement from 550 feet to surface, which was allowing shallow Ohio Shale gas to enter the annulus. A good to excellent bond was measured below that depth. (Ohio DNR DMRM, 2008; Bair et al, 2010)

Primary Causes of Gas Invasion into Drinking Water Aquifers

1. **Poor Primary Cement Job**: The poor primary cement job left the shallow Newburg Dolomite and Ohio Shale gas-bearing zones open to the annulus behind the production casing, allowing high-pressure gas to migrate into the annulus.
2. **Decision to Hydraulically Fracture the Well Despite the Poor Cement Job**: Circulation of fluid and oil in the surface-production casing annulus during hydraulic fracturing indicates that the fractures grew “out-of-zone” and allowed the frac to communicate directly with the wellbore. The frac likely compromised the 80 feet of cement between the top perf and the open annulus, causing a loss of cement bond between the formation and production casing. This likely allowed Clinton gas to also migrate into the annulus behind the production casing.
3. **Shutting in the Well for 31 Days**: The decision to shut in the surface-production casing annulus for 31 days allowed the annulus to become over-pressured and gas to migrate from the high-pressure annulus, through fractures, to the groundwater aquifer and eventually into domestic water wells. (Ohio DNR DMRM, 2008; Bair et al, 2010)

Areas of Dispute

Subsequent to the well contamination incident, 42 property owners brought a suit against OVESC and six other parties involved in the operations at the English No. 1 well. (Bair et al, 2010). As part of the suit, the attorneys for the plaintiffs contracted Eckstein & Associates (E&A), a geological engineering firm, to review the causes of the incident. This subsequent report differed from the DMRM assessment in several areas. Consequently, DMRM convened a panel of experts to review the findings of Eckstein & Associates. The four main areas of dispute are as follows:

1. Was the over-pressurization of the annulus of sufficient magnitude to induce fractures in the geologic formations exposed in the uncemented annulus?

    a. The E&A report concluded that the pressures were indeed sufficient to create fractures in the Ohio Shale and portions of the “Big Lime”, providing migration pathways for deep gas. (Eckstein, 2009)
    b. The DMRM Expert Panel concluded that the pressures may have been sufficient to create fractures in the Ohio Shale but that any fractures created would be shallow, oriented horizontally, and of limited extent, and at most would temporarily augment transport along natural fracture networks. (Bair et al, 2010)
2. If the over-pressurization of the annulus did induce fractures, could they become permanent migration pathways for deep gas to reach groundwater?
    a. The E&A report concluded that the “deep- and far-reaching fractures” created by the over-pressurization of the annulus will serve as long-term migration pathways for methane to groundwater. Supporting evidence offered includes data for wells in the affected area showing that methane concentrations have remained high or increased over time. (Eckstein, 2009)
    b. The DMRM Expert Panel report concluded that any induced fractures would be shallow and of limited vertical, aerial, and temporal extent and consequently would not create long-term migration pathways for gas to groundwater. Supporting evidence offered includes data showing that the gas plume is dissipating upward and gas pressures in affected wells are decreasing. (Bair et al, 2010)
3. Can methane concentrations in domestic water wells be used to delineate such fracture networks?
    a. The E&A report concluded that the presence of methane in water wells was sufficient evidence for the presence of induced fractures, and therefore could be used to map or delineate such fracture networks. (Eckstein, 2009)
    b. The DMRM Expert Panel report concluded that the presence of methane alone, in the absence of other corroborating evidence, was not sufficient to delineate such fracture networks. They determined that other factors are in part responsible for the patterns of methane concentrations measured in domestic water wells over time. (Bair et al, 2010)
4. What is the nature and origin of the presence of black particulate matter in some domestic water wells?
    a. Following the English No. 1 well incident, some residential water wells began yielding black particulate matter. Chemical analysis showed that the particles consist of heavy metals, including lead and copper. The E&A report concluded that the particulate matter was entrained in the gas leaking from the well, with the likely source being the Ohio Shale. (Eckstein, 2009)

b. The DMRM report concluded that the particulate matter was not widespread and that it could not be determined whether it was created by the released methane or by natural processes. (Bair et al, 2010)

Case Study #2: Mamm Creek Field, Garfield County, Colorado

Incident Summary and Studies Considered for Review

In 2004, citizens notified the Colorado Oil and Gas Conservation Commission (COGCC) of the presence of gas bubbling in the West Divide Creek, Garfield County, CO, near the Mamm Creek Gas Field. Subsequent investigations identified the gas as thermogenic gas from the Williams Fork (Mesaverde) Formation, which is the primary gas-bearing target in the Mamm Creek Field. Water testing also detected the presence of BTEX compounds above regulated limits. It was determined that the gas and other contaminants were leaking from a nearby wellbore which had been improperly cemented, Encana's Schwartz #2-15B. Fines from this incident were used to fund a study to determine the vulnerability of groundwater and surface water to impacts from natural gas exploration and other human activities in Garfield County, CO near the Mamm Creek Natural Gas Field.

The Phase I study, performed by URS Corporation, compiled and evaluated existing data on water wells, gas wells, and water quality, and also included a limited amount of new field work (URS, 2006). The Phase II Study, performed by S.S. Papadopulos and Associates, focused on two field sampling tasks:

1. Water quality, gas composition, and methane stable isotope samples were obtained for wells which previously had compounds of concern above regulated limits or had sodium-chloride (Na-Cl) concentrations which suggested mixing with deeper brine/saline water.
2. Produced water and gas samples were taken from gas wells near the domestic water wells which had water and/or gas chemistry which may have been influenced by deeper formations, either by natural processes or through gas drilling activities (Papadopulos, 2008)

Subsequently, Dr. Geoffrey Thyne provided summaries and reviews of the Phase I and Phase II studies (Thyne, 2008). Dr. Thyne's conclusions were in turn reviewed by S.S. Papdopulous and Associates (Papadopulos, 2009), Bill Barrett Corporation (Donato et al, 2009), and Dr. Anthony Gorody of Universal Geoscience Consulting, Inc (Gorody, 2009).

Beginning in 2009 and completed in 2011, the United States Geological Survey (USGS), in cooperation with the Colorado Department of Public Health, undertook a study to determine the sources and sinks of nitrate and methane in domestic water wells screened in the shallow Wasatch formation in Garfield County (McMahon et al, 2011).

The following findings were generally consistent throughout all the studies considered:

1. Some domestic water wells had increased concentrations of methane, relative to background
    a. Both biogenic and thermogenic methane were detected
2. Some domestic water wells had concentrations of fluoride, selenium, nitrate, and/or arsenic which exceeded health-based standards
    a. Fluoride and selenium concentrations do not appear to be related to oil and gas activity
    b. Nitrate concentrations are most likely related to agricultural activity, septic system effluent, and/or animal waste
3. Some domestic water wells had concentrations of chloride, iron, manganese, and/or total dissolved solids (TDS) which exceeded aesthetic-based standards
    a. High chloride and TDS concentrations indicate the mixing or interaction of shallow groundwater with deeper formation water. (URS, 2006; Papadopulos, 2008; Thyne, 2008; McMahon et al, 2011)

Several areas of dispute arose between the various studies, including:

1. Evidence for a temporal correlation of methane and chloride contamination and natural gas activity
2. The nature and origin of methane in domestic water wells
3. The primary mechanism for deep Wasatch or Mesaverde formation water to mix with shallow groundwater (URS, 2006; Papadopulos, 2008; Thyne, 2008; Donato et al, 2009; Gorody, 2009; Papadopulos, 2009; McMahon et al, 2011)

Areas of Dispute

Evidence for a temporal correlation of methane and chloride contamination and natural gas activity

In his review of the Phase I and II studies, Dr. Thyne observed that methane concentrations and the number of wells with elevated chloride concentrations increased with time and were correlated to the increasing number of gas wells with time. (Thyne, 2008) Papadopulos and Associates, Bill Barrett Corporation, and Dr. Gorody disputed this claim and stated that there is no statistically significant increase in methane or chloride concentrations with time (Donato et al, 2009; Gorody, 2009; Papadopulos, 2009).

The nature and origin of methane in domestic water wells

The Phase I study found the presence of methane of biogenic, thermogenic, and unknown origin in the water samples. Most samples that had elevated concentrations of methane contained biogenic methane. The study indicates that biogenic methane can be formed by various processes but does not offer a hypothesis for how the methane came to be present in groundwater and domestic water wells. The implication, however, is that presence of biogenic methane in domestic water wells is not related to oil and gas development. A smaller number of samples contained thermogenic methane. In the area near the West Divide Creek seep, the origin of the methane is concluded to be from the leaking gas well which caused the seep. Some of the highest methane concentrations were detected in the southeastern portion of the study area. Although there had been little gas development activity in the area, there were several old wellbores that records indicate may not have been properly plugged and abandoned. The study concluded that the presence of thermogenic methane in water samples could result from either migration along natural pathways, such as faults, or from natural gas drilling, completion, or production activities or improperly abandoned wells. The researchers concluded that more data would be necessary to conclusively determine which migration pathway was responsible in each instance. The origin of the unknown methane types could not be determined and may have resulted from mixing of different sources. (URS, 2006)

The Phase II study also found the presence of methane of both biogenic and thermogenic origin in domestic water wells. Although most samples had isotopic compositions which indicated a thermogenic origin, researchers determined that most samples were in fact biogenic in origin. The conclusion was that the majority of samples which appeared to have a thermogenic isotopic signature had undergone a “biogenic methane oxidation shift”. This is a process by which gas that is biogenic in origin undergoes oxidation, leaving the remaining fraction of methane with an isotopic signature that appears to be thermogenic but is in fact biogenic. As with Phase I, the researchers did not offer a hypothesis for how the biogenic methane came to be present in domestic water wells. Again, the implication is that the presence of biogenic methane in domestic water wells is not related to oil and gas development. A smaller number of samples contained methane that the researchers believed to be truly thermogenic in origin. Two hypotheses were offered to explain the nature and origin of these samples:

1. The samples may be derived from deeper gas-bearing formations, either tight sands gas or coalbed methane gas
2. The samples may represent some mixture between biogenic and thermogenic gas

For those samples which the study determined to be truly thermogenic in origin, and not the product of oxidation of biogenic methane, the researchers suggest that two mechanisms may be responsible: migration along natural faults and fractures or gas exploration and production. The study concluded that distinguishing between the two is not possible with the current data. (Papadopulos, 2008)

In his review of the Phase I and Phase II studies, Dr. Thyne also agreed that the samples contained methane which appeared to be of both biogenic and thermogenic origin. However, unlike the previous researchers, Dr. Thyne concluded that the majority of samples were thermogenic in origin. Dr. Thyne rejected the conclusion of the Phase II study that many of the samples with thermogenic isotopic signatures were in fact biogenic methane which had been oxidized. For those samples with isotopic values indicating biogenic origin, Dr. Thyne noted that their origin was microbial CO_2 reduction, in which CO_2 is converted to methane by microbial processes. Dr. Thyne concluded that the origin of this CO_2 was thermogenic CO_2 from the Williams Fork (Mesaverde) Formation. Consequently, the methane produced by this CO_2 would also be considered thermogenic in origin. Due to this finding that the majority of samples were thermogenic in origin, Dr. Thyne concluded that gas development activities had impacted groundwater. (Thyne, 2008) Papadopulos and Associates disputed these conclusions and found no basis to change the conclusions from their original report (Papadopulos, 2009).

The USGS study also sampled methane which appeared to be of both biogenic and thermogenic origin. The USGS study used a more diverse geochemical data set than previous studies to determine the nature and sources of the methane. Samples with the highest concentrations of methane appeared to be biogenic in origin. These samples also contained high concentrations of helium-4 and the co-occurrence implies that the methane was derived from a deep source rather than being generated in-situ in domestic water wells. Researchers concluded that one source for this deep biogenic methane could be the deep Wasatch Formation. Some samples also contained methane which appeared to be thermogenic in origin. Researchers determined that some of these samples may have contained biogenic methane which had undergone oxidation while other samples contained methane which was truly thermogenic in origin. The source of this thermogenic gas was most likely the Mesaverde (Williams Fork) Formation. The study concluded that two migration pathways were possible for both the deep biogenic and thermogenic gas: natural faults or fractures or the uncemented annular space in gas wells. (McMahon, et al, 2011)

The primary mechanism for deep Wasatch or Mesaverde formation water to mix with shallow groundwater

All four studies concluded that the geochemistry of some water samples may indicate mixing between shallow groundwater and deeper water. All four studies also suggested that either natural faults or fractures or gas wellbores could provide pathways for deep water to reach shallow water, however there was some disagreement between the studies on which of these pathways was most likely. (URS, 2006; Papadopulos, 2008; Thyne, 2008; McMahon et al, 2011)

The URS study concluded that the cause of mixing could not be determined and could have been the result of either natural pathways or gas development activities (URS, 2006). The Papadopulos and Associates study also concluded that natural pathways, wellbores, or hydraulic fractures may be possible migration pathways for deeper fluids but stated that the samples with geochemical signatures indicating mixing were from wells in areas with only modest gas development activity and therefore it was not possible to distinguish between natural and manmade impacts (Papadopulos, 2008). In his review of the Phase I and Phase II study, Dr. Thyne concluded that the number of domestic water wells with elevated chloride concentrations was increasing over time and correlated to the number of gas wells drilled, and the that source of the chloride was produced water (Thyne, 2008). The USGS study concluded that both natural fractures and wellbores were likely migration pathways for deeper formation water to reach shallow groundwater. They also determined that Mesaverde formation water was an important source of chloride in some wells even when the actual fraction of Mesaverde water in the sample was small (McMahon et al, 2011).

Key Observations

Despite the areas of dispute discussed above, some key observations and conclusions emerged from the studies. (URS, 2006; Papadopulos, 2008; Thyne, 2008; McMahon et al, 2011)

- Some domestic water samples contain methane and deep formation water which may have migrated to water wells through either natural pathways or gas wellbores or both.
- The study area is naturally faulted and fractured. Fault and fracture density increases near structural features, such as the Divide Creek Anticline.
- Regulations were updated in 2004 to require that all new wells have surface casing set below the lowest USDW and cemented to surface and production casing cemented to 500’ above the top of gas in the Mesaverde (Williams Fork) Formation. There is no requirement to cement over the deep Wasatch Formation. Older wells may have been constructed using different standards and may not have been properly abandoned.
- Gas production wells with persistent or recurring elevated bradenhead pressures have been identified near structural features.
- Domestic water wells with elevated methane and chloride concentrations are often coincident with structural features.
- Natural fractures and faults may provide migration pathways for gas and fluids, both to groundwater and to the uncemented annular space of wellbores. Fractures and faults may also cause complications in well drilling, construction, and completion and result in well integrity problems.

Challenges

Both these case studies and others around the country face challenges in determining causality of water contamination. One of the most significant challenges is the fact that in many oil and gas development fields, a systematic and comprehensive assessment of baseline water quality predating oil and gas development does not exist. When water contamination related to oil and gas development is suspected, investigators must piece together baseline water quality from previous studies and reports or try to sample water which may be “outside” the influence of oil and gas development.

Determining the extent and source of water contamination is also challenging. As noted by Dr. Thyne, domestic water wells may not be ideally located to robustly determine the source of contamination. (Thyne, 2008) As pollutants disperse from their source, they may undergo chemical or physical changes, making it difficult to conclusively determine the source of pollution. Pollutants and contaminants may also interact with any media between the source and water well and result in the mobilization of naturally occurring contaminants. When such naturally occurring contaminants are detected in groundwater, it may be difficult to distinguish whether they migrated as a result of natural or anthropogenic causes or the potential link between naturally occurring contaminants and human activities may not be investigated.

Selecting the proper set of test parameters to determine the source of water contamination is also a challenge. As seen in the Garfield County example, many of the chemicals tested for in the water samples could not be used to conclusively identify the source or method of transport of contaminants because they were indicative of multiple sources and/or migration pathways.

While it is unlikely that any water contamination investigation will test for all chemicals used or released by oil and gas drilling, special care must be given to selecting proper indicator chemicals. In these and other examples, investigators often assume that the presence of biogenic gas in drinking water is not related to oil and gas activities and that thermogenic gas is related to oil and gas activities. As shown in the USGS study, this is a poor assumption. Investigators must take the next steps and determine both the source of methane in groundwater and the mechanisms by which it could migrate from its source into groundwater.

One of the most significant concerns regarding the risk of hydraulic fracturing to contaminate drinking water is that many of the chemicals used in hydraulic fracturing fluid are not known on a well by well basis. In the Bainbridge, OH case, investigators tested for three chemicals which were present in the hydraulic fracturing fluid used to frac the English No. 1 well (Ohio DNR DMRM, 2008). However, the report did not state how many chemicals in total were used in the hydraulic fracturing fluid or whether those they selected to test for represented the range of mobility and/or toxicity of all the chemicals used. In the Garfield County example, none of the studies tested the water for chemicals used in hydraulic fracturing. In their recommendations for additional work, Papadopulos and Associates stated, "The effect on groundwater due to the introduction of drilling or well completion/hydrofracturing fluids into the shallow aquifer was not investigated for this study. A study evaluating possibly local effects of drilling or hydrofracturing fluids on domestic groundwater should be considered." (Papadopulos, 2008) Given that all studies found that deeper groundwater mixed with shallow water and that natural fractures or wellbores could provide the pathways for this contamination, testing for the presence of hydraulic fracturing chemicals and determining how induced fractures could interact with natural fractures is an extremely important piece of additional research which should be conducted.

Solutions and Lessons Learned

Detailed site characterization and planning and baseline testing prior to any oil and gas development are crucial. An integral part of understanding how wellbore construction and integrity and hydraulically induced fractures could create migration pathways to and potentially contaminate groundwater is a thorough understanding of the current geologic and hydrologic regimes. Site characterization and planning work may include but are not limited to:

- Detailed study of regional and local geologic structure including faults, fractures, stress regimes, rock mechanical properties, etc. through the use of 3D seismic surveys, outcrop analog studies, collection of core and relevant analysis, well logs including FMI/image logs, etc. As seen in Garfield County, the presence of natural faults and fractures and areas of increased fracturing around structural features may be pathways for gas, drilling fluids, hydraulic fracturing fluids or formation fluids to reach groundwater or the uncemented annuli of hydrocarbon wells and may also compromise wellbore integrity.
- Detailed pre-drill maps of the extent and chemical composition of groundwater aquifers
- Hydrologic flow and transport data collection and modeling

- Thorough identification of existing wellbores, determination of the integrity of those wellbores (i.e. casing, cement, etc.), and mitigation where necessary
- Hydrocarbon sampling and analysis to determine variations in chemical and isotopic compositions of any hydrocarbons which may be encountered both vertically in a wellbore and aerially throughout an oil or gas field

As development of an oil or gas field proceeds, these data sets must be continually updated as new information becomes available, both temporally and aerially.

Wellbore construction and integrity are paramount in protecting drinking water. Wellbores must be constructed so that any hydrocarbon or non-potable water bearing formations are isolated. As seen in Garfield County and in other examples throughout the country, shallow gas-bearing zones can be significant sources of methane in drinking water. Shallow brine or formation water or its chemical constituents may also migrate into drinking water if not isolated. Hydraulic fracturing must not occur if wellbore integrity is in question.

Wellbore maintenance is also crucial. Older wellbores which have degraded, been constructed using less protective standards, or which have been improperly abandoned must be identified and remediated. Such wellbores could provide migration pathways for contaminants to reach groundwater and hydraulically induced fractures could provide new or enhanced migration pathways for gas or fluids to reach these wellbores.

A water quality monitoring program should be developed and implemented throughout the life of oil and gas exploration and production. The use of dedicated water quality monitoring wells should be considered in order to help detect the presence of contaminants prior to their reaching domestic water wells. Placement of such wells should be based on detailed hydrologic flow models and the distribution and number of hydrocarbon wells.

Robust models and direct measurements of hydraulic fracture growth, including preferred fracture orientation, frac half-length, and frac height growth, are also crucial. Techniques such as microseismic monitoring, tiltmeters, and chemical and radioactive tracers should be employed over the life of the field, especially as development progresses into new areas.

Equally critical is robust post-frac monitoring. This includes tracking injected volumes of frac fluids as well as flowback volumes to better understand the potential for migration. In order to effectively monitor where frac fluids go and whether they or the chemicals they contain interact with groundwater, it is essential to know the exact chemical composition of all constituents involved in the drilling and completion process, including but not limited to:

- Drilling fluids/mud
- Frac fluid
- Connate water/produced water
- Geochemistry of producing formations and formations which serve as potential barriers between the producing formation and any aquifer

Cumulative impacts must also be considered. The risks to groundwater may increase as development progresses, as older wellbores are abandoned, and as drilling expands to new areas. The impacts of increasingly more wellbores and increased fracture density due to hydraulic fracturing and the potential impacts to drinking water must be examined.

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